have such a distribution. Disk models produce unacceptable quadrupole moments for distant sources or unacceptable $\langle V/V_{max}\rangle$ for nearby sources[14]. Galactic halo distributions[15] must be at least 50 kpc in radius without strong central condensation to satisfy the BATSE limits on the dipole moment. Populating a halo with neutron stars (the currently favoured candidates) may prove difficult. Nearby extragalactic models will have difficulty with the lack of correlations with M31 and the Virgo cluster[16]. The isotropy and V/V_{max} results can be reproduced by cosmological models[17,18], which require isotropy but yield $V/V_{max}<0.5$ because of redshift effects. These models will require further development to address details of the burst phenomenon, such as energy spectra, occurrence rate and luminosity. □

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1. Fishman, G. J. *et al.* in *Proc. Gamma Ray Observatory Science Workshop* (ed. Johnson, W. N.) 39–50 (NASA/GSFC, Greenbelt, 1989).
2. Golenetskii, S. *Adv. Space Res.* **8(2)**, 653–657 (1988).
3. Schmidt, M., Higdon, J. C. & Hueter, G. *Astrophys. J.* **329**, L85–87 (1988).
4. Atteia, J.-L. *et al. Nature* **351**, 296–298 (1991).
5. Ogasaka, Y., Murakami, T., Nishimura, J., Yoshida, A. & Fenimore, E. E. *Astrophys. J.* (in the press).
6. Mazets, E. *et al. Astrophys. Space Sci.* **80**, 1–143 (1982).
7. Matz, S. *et al.* in *Proc. Los Alamos Workshop on Gamma Ray Bursts* (eds Ho, C. Epstein, R. & Fenimore, E. E.) (Cambridge University Press, in the press).
8. Chuang, K. W., White, R. S., Klebesadel, R. W. & Laros, J. G. *Astrophys. J.* (in the press).
9. Hartmann, D., & Epstein, R. I. *Astrophys. J.* **346**, 960–966, (1989).
10. Brock, M. N. *et al.* in *Proc. Gamma Ray Bursts 1991* (eds Fishman, G. J. & Paciesas, W. S.) (in the press).
11. Cline, T. L. *et al.* in *Proc. Gamma Ray Bursts 1991* (eds Fishman, G. J. & Paciesas W. S.) (in the press).
12. Hurley, K. *et al.* in *Proc. GRO Annapolis Workshop* (in the press).
13. Schoenfelder, V. *et al. IAU Circ.* No. 5369 (1991).
14. Paczynski, B. *Astrophys. J.* **348**, 485–494, (1990).
15. Brainerd, J. J. *Nature* (in the press).
16. Atteia, J.-L. & Hurley, K. *Adv. Space Res.* **6(4)**, 39–43, (1986).
17. Paczynski, B. *Acta Astr.* **41**, 157–166 (1991).
18. Paczynski, B. *Acta Astr.* **41**, (in the press).

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A planetary system around the millisecond pulsar PSR1257+12

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MILLISECOND radio pulsars, which are old ($\sim 10^9$ yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars[1]. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257+12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 $M_\oplus$ and 3.4 $M_\oplus$, where $M_\oplus$ is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby ($\sim$500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829−10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-like bodies.

The 6.2-ms pulsar PSR1257+12 (Fig. 1) was discovered during the search at high galactic latitudes for millisecond pulsars conducted in February 1990 with the 305-m Arecibo radiotelescope at a frequency of 430 MHz (ref. 2). The characteristics of this survey and the details of data analysis are described elsewhere[4]. The confirming observations made on 5 July 1990 have been followed by routine pulse timing measurements of the new pulsar. A total of 4,040 pulse time-of-arrival (TOA) observations have been accumulated so far, with the Arecibo radiotelescope, the 40-MHz, three-level correlation spectrometer and the Princeton Mark III pulsar processor at 430 MHz and 1,400 MHz. A typical uncertainty in the TOAs derived from 1-min pulse integrations is $\sim 15\ \mu$s.

The standard analysis of the timing data has been carried out using the model fitting program TEMPO[5] and the Center for Astrophysics Solar System ephemeris PEP740R. With a growing time span of the TOA measurements, it had gradually become clear that the TOAs showed an unusual variability superimposed on an annual sinusoidal pattern caused by a small ($\sim 1'$) error in the assumed pulsar position. To separate these effects unambiguously, a timing-independent, interferometric position of PSR1257+12 was measured with the Very Large Array (VLA) in its A-array configuration on 19 July and again on 18 September 1991. The $\sim 0.1''$ accuracy of the resulting pulsar position was achieved by referencing the fringe phase to a point-source calibrator 1.7° away.

A least-squares fit of a simple model, which involved the pulsar's rotational period, P, and its derivative, $\dot{P}$, as free parameters and the fixed VLA position (Table 1), to the timing data spanning the period of 486 days resulted in post-fit residuals shown in Fig. 2*a*. The residuals, which measure the difference between the predicted and the actual TOAs, show a quasiperiodic 'wandering' over the entire pulsar period. A closer examination of this effect has revealed that it was caused by two strict periodicities of 66.6 and 98.2 days in the pulse arrival times. This is further demonstrated in Fig. 2*b* and *c*, which shows post-fit residuals after fitting each of the two periods separately to the above data, assuming simple keplerian binary models involving a low-mass binary companion to the pulsar. Evidently, fitting for one of the assumed binary periods leaves the other one as a post-fit residual, implying that the pulse arrival times of PSR1257+12 are indeed affected by two independent periodicities. Further detailed analysis has shown that the periodicities are independent of radio frequency and that other millisecond pulsars routinely observed at Arecibo with the same data acquisition equipment show no such effect in their timing residuals.

Millisecond pulsars are extremely stable rotators. Systematic timing observations of objects like the 1.5-ms pulsar 1937+21 (ref. 6) have not revealed any timing noise, quasiperiodic TOA variations or 'glitches' at the level often found in the population of younger pulsars and believed to be related to neutron star seismology[7]. The frequency independence of the amplitude of

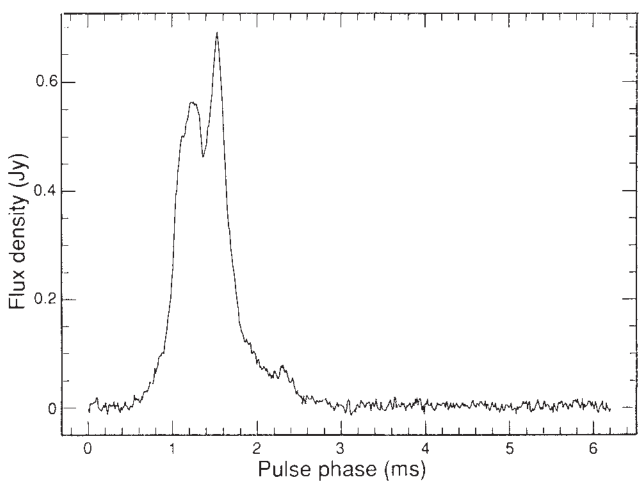


FIG. 1. The average pulse profile of PSR1257+12 at 430 MHz. The effective time resolution is $\sim 12\ \mu$s.

TABLE 1 Parameters of the PSR1257 +12 system

Pulsar parameters		
Rotational period, P	0.00621853193177 ± 0.00000000000001 s	
Period derivative, $\dot{P}$	$1.21 \times 10^{-19} \pm 2 \times 10^{-21}$ s s^{-1}	
Right ascension (B1950.0, VLA)	12 h 57 min 33.131 s ± 0.015	
Right ascension (B1950.0, timing)	12 h 57 min 33.126 s ± 0.003	
Declination (B1950.0, VLA)	12° 57′05.9″ ± 0.1	
Declination (B1950.0, timing)	12° 57′06.60″ ± 0.02	
Epoch	JD 2448088.9	
Dispersion measure	10.18 ± 0.01 pc cm^{-3}	
Flux density (430 MHz)	20 ± 5 mJy	
Flux density (1,400 MHz)	1.0 ± 0.2 mJy	
Surface magnetic field, B	8.8×10^8 G	
Characteristic age, τ_c	0.8×10^9 yr	
Keplerian orbital parameters		
Projected semimajor axis, $a_1 \sin i$	1.31 ± 0.01 light ms	1.41 ± 0.01 light ms
Eccentricity, e	0.022 ± 0.007	0.020 ± 0.006
Epoch of periastron, T_0	JD 2448105.3 ± 1.0	JD 2447998.6 ± 1.0
Orbital period, P_b	5751011.0 ± 800.0 s	8487388.0 ± 1800.0 s
Longitude of periastron, ω	252° ± 20°	107° ± 20°
Parameters of the planetary system		
Planet mass, $m_{2,3}$ ($M_\oplus$)	3.4/sin i	2.8/sin i
Distance from the pulsar, d (AU)	0.36	0.47
Orbital period, P_b (days)	66.6	98.2

TOA variations in PSR1257+12 rules out propagation phenomena, such as those detected in eclipsing binary pulsars[8,9], as a possible source of the observed periodicities. The integrated pulse profiles of PSR1257+12 do not show any morphological changes that might indicate the presence of a free precession of the pulsar spin axis[10,11] or any magnetospheric phenomena at the level that could lead to periodic TOA variations of the measured magnitude. Consequently, the most plausible remaining alternative is that PSR1257+12 has two low-mass companions and that their orbital motion is responsible for the observed TOA variations.

To analyse this exciting possibility further, we have modified the code of the TEMPO program to accommodate a timing model including multiple, noninteracting keplerian orbits. The result of a fit of the model including the rotational and positional parameters of the pulsar as well as the two, five-parameter keplerian orbits to the entire data set is shown in Fig. 2*d*. The post-fit r.m.s. residual of the resultant timing model is ~18 μs (comparable to the individual TOA uncertainties) and the remaining residuals contain very little systematic variation. The model parameters of the pulsar and its assumed two companions are listed in Table 1. The derived parameters have been obtained from standard considerations involving very low-mass objects in keplerian orbits around a $1.4 M_\odot$ neutron star. The pulsar period variations predicted by this model are displayed in Fig. 3 together with the observed period values derived from timing data. Note that the presence of the planet-sized bodies orbiting the pulsar results in apparent period variations of only ±15 ps. This is caused by the pulsar's spatial motions which are characterized by the projected maximum velocity and displacement amplitudes of ±0.7 ms^{-1} and ±900 km, respectively.

The high quality of the two-companion model fit to the pulsar timing data covering several orbital cycles provides compelling evidence that PSR1257+12 possesses a planetary system consisting of at least two planet-sized bodies. The possibility of more planets around PSR1257+12 is indicated by a 0.7″ discrepancy between the VLA and the timing positions, which is considerably greater than the conservative error estimates (Table 1). This discrepancy may arise from a bias in the timing position caused by a presence of a third planet with orbital period close to one year. Because the currently measured value of the second period derivative, $\ddot{P}$, of the pulsar is not significant, the effect of any outer planets that could be present in the 1257+12 system would be entirely absorbed in $\dot{P}$.

The characteristics of the 1257+12 planets are not unlike those of the inner Solar System. Both planets circle the pulsar at distances similar to that of Mercury in its orbit around the Sun. Assuming a random distribution of the inclinations, i, of orbital planes, there is a 50% probability that $i \geq 60°$, so that the median values of the permissible masses are $3.2 M_\oplus$ and $3.9 M_\oplus$, respectively (see Table 1). Interestingly, the ratio of orbital periods, 1.476 ± 0.001, is close to a 3/2 orbital resonance of the type often encountered in the Solar System, either between planetary satellites, between Jupiter and some asteroids, or even Neptune and Pluto[12]. Also, the similarity of the measured eccentricities combined with the ~180° separation of the pericentres of the orbits can be easily understood in terms of secular perturbations of the orbital elements of the two planets (see, for example ref. 13). Finally, a hypothetical energy flux at the planets' distance from the pulsar (~0.4 AU) due to the neutron star's rotational energy loss ($\dot{E} = I\omega\dot{\omega}$, where I is the moment of inertia and $\omega = 2\pi/P$) is ~4×10^7 erg cm^{-2} s^{-1}. This is ~30 times the solar constant and corresponds to a black-body temperature of ~670 K, which is similar to the measured dayside surface temperature of Mercury (see, for example, ref. 14).

The possibility of the existence of planet-sized bodies orbiting neutron stars has been contemplated in the past[15,16]. The most recent evidence has been presented by Bailes *et al*[3], who have detected a ~6-month periodicity in the timing residuals of a relatively young pulsar, PSR1829−10, which is interpreted in terms of the orbital motion of a ~10 $M_\oplus$ companion. A number of mechanisms have been proposed to explain a planet around PSR1829−10 (refs 17–21). In the case of PSR1257+12, its old age and a low surface magnetic field (Table 1) are typical of neutron stars which are believed to evolve in low-mass binary systems and are spun up to the observed millisecond periods by accretion of matter from their stellar companions[1]. As it is not very likely that any primordial planets would survive this

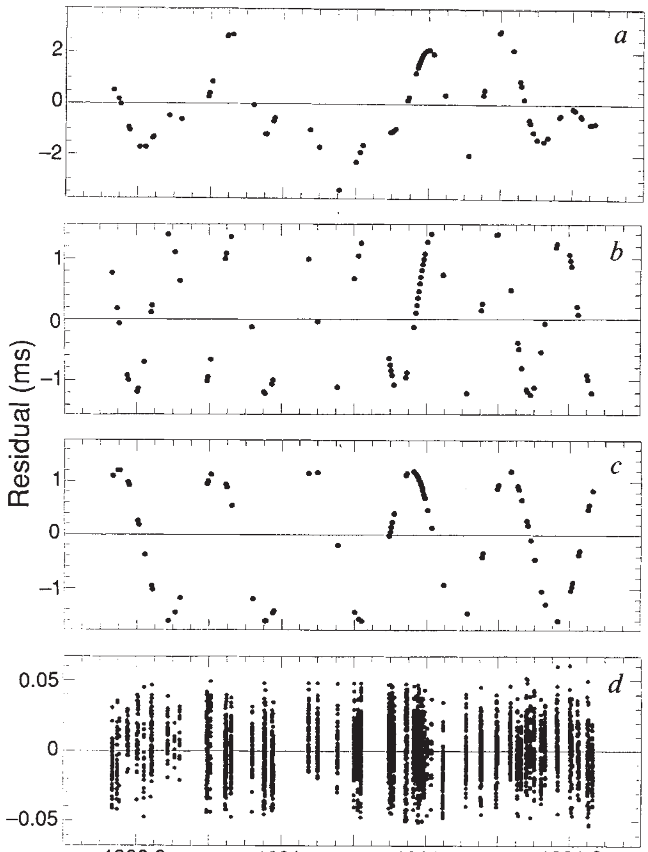


FIG. 2 The post-fit residuals of pulse arrival times from PSR1257 +12. *a*, Fit for rotational parameters only (VLA position of the pulsar fixed); *b*, fit for a 98.2-day keplerian orbit (leaves a 66.6-day periodicity as residual); *c*, fit for a 66.6-day keplerian orbit (leaves a 98.2-day periodicity as residual); *d*, fit for all parameters of *a*–*c*.

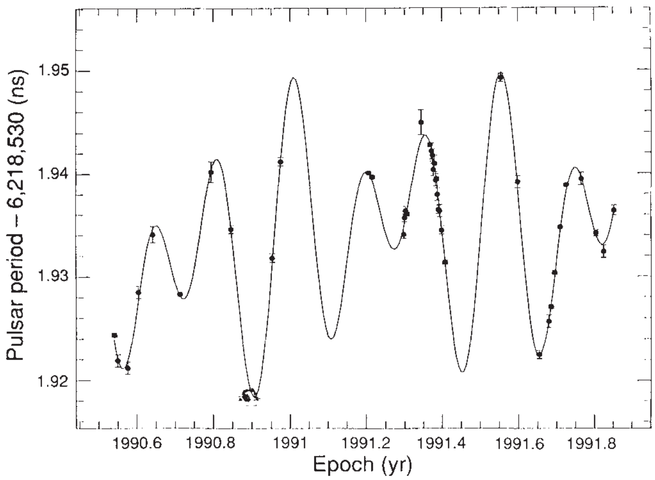


FIG. 3 Period variations of PSR1257+12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257+12 system.

kind of evolution[22], the observed 1257+12 system probably consists of 'second generation' planets created at or after the end of the pulsar's binary history. Because a second supernova explosion is not expected to occur in a low-mass binary, such planets could form a stable system of bodies orbiting an old neutron star. Another important evolutionary constraint is provided by the observed very low eccentricities ($e \approx 0.02$) of the planetary orbits and the near-resonance ratio of the orbital periods. These characteristics suggest that the planets were created from some form of accretion disk that would naturally provide means to circularize the orbits and to bring them close to a 3/2 resonance[12]. Consequently, it seems that any plausible mechanism for the creation of a planetary system around a millisecond pulsar must provide a way to remove its stellar companion in a manner different from the disruption of a binary system caused by a supernova explosion and to retain enough circumpulsar matter to form planet-sized objects.

Within the constraints provided by the observational evidence, it is tempting to postulate that the 1257+12 system simply represents one of the possible outcomes of a neutron star evolution in a low-mass binary system[1]. As two examples of companion-star evaporation by millisecond pulsars have already been detected[7,8], this mechanism seems to account naturally for the absence of such a companion to PSR1257+12. In this case, one way to supply the material for planet creation could be a disk formed out of the ablated stellar matter ejected from the binary system[23,24]. The existence of such an 'outer disk' around the eclipsing binary pulsar PSR1957+20 could explain the observed orbital decay of this system[25].

The results described here strongly suggest that one of the nearby galactic millisecond pulsars, PSR1257+12, is accompanied by a system of two or more planet-sized bodies. The pulse timing method (similar to the analysis of single-line spectroscopic binaries) was used to detect a $\pm 0.7\ \mathrm{m\,s^{-1}}$ pulsar 'wobble' caused by orbital motions of the planets. In fact, planetary masses smaller than that of the Moon could easily be detected with this technique. At present, this kind of accuracy is entirely inaccessible to the optical methods of planetary system detection[26]. The existence of both the 1257+12 planetary system and the object orbiting the pulsar PSR1829−10 seems to suggest that planets can form under a variety of conditions. This notion and the possibility of a non-negligible frequency of occurrence of planets around neutron stars, if confirmed, will have far-reaching consequences for our understanding of the formation and evolution of planetary systems and for future strategies of searches for planets outside the Solar System. □

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1. Bhattacharya, D. & van den Heuvel, E. P. J. *Phys. Rep.* **203**, 1-124 (1991).
2. Wolszczan, A. *IAU Circ.* No. 5073 (1990).
3. Bailes, M., Lyne, A. G. & Shemar, S. L. *Nature* **352**, 311-313 (1991).
4. Wolszczan, A. *Nature* **350**, 688-690 (1991).
5. Taylor, J. H. & Weisberg, J. M. *Astrophys. J.* **345**, 434-450 (1989).
6. Davis, M. M., Taylor, J. H., Weisberg, J. M. & Backer, D. C. *Nature* **315**, 547-550 (1985).
7. Alpar, M. A., Nandkumar, R. & Pines, D. *Astrophys. J.* **311**, 197-213 (1986).
8. Fruchter, A. S., Stinebring, D. R. & Taylor, J. H. *Nature* **333**, 237-239 (1988).
9. Lyne, A. G. *et al. Nature* **347**, 650-652 (1990).
10. Shaham, J. *Astrophys. J.* **214**, 251-260 (1977).
11. Nelson, R. W., Finn, L. S. & Wasserman, I. *Astrophys. J.* **348**, 226-231 (1990).
12. Peale, S. J. *Ann. Rev. Astr. Astrophys.* **14**, 215-246 (1976).
13. Dermott, S. F. & Nicholson, P. D. *Nature* **319**, 115-120 (1986).
14. Vilas, F. in *Mercury* (eds Vilas, F., Chapman, C. R. & Matthews, M. S.) 59-76 (University of Arizona Press, Tucson, 1988).
15. Richards, D. W., Pettengill, G. H., Counselman, C. C. III & Rankin, J. M. *Astrophys. J.* **160**, L1-6 (1970).
16. Demiański, M. & Prószyński, M. *Nature* **282**, 383-385 (1979).
17. Podsiadlowski, Ph., Pringle, J. E. & Rees, M. J. *Nature* **352**, 783-784 (1991).
18. Fabian, A. C. & Podsiadlowski, Ph. *Nature* **353**, 801-801 (1991).
19. Lin, D. N. C., Woosley, S. E. & Bodenheimer, P. H. *Nature* **353**, 827-829 (1991).
20. Krolik, J. H. *Nature* **353**, 829-831 (1991).
21. Wasserman, I., Cordes, J. M., Finn, L. S. & Nelson, R. W. *Cornell Univ. preprint* (1991).
22. Nakano, T. *Mon. Not. R. astr. Soc.* **224**, 107-130 (1987).
23. Shu, F. H., Lubow, S. H. & Anderson, L. *Astrophys. J.* **29**, 223-241 (1979).
24. Rudak, B. & Paczyński, B. *Acta Astr.* **31**, 13-24 (1981).
25. Ryba, M. F. & Taylor, J. H. *Astrophys. J.* **380**, 557-563 (1991).
26. Black, D. C. *Space Sci. Rev.* **25**, 35-81 (1980).

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Birth of a radio supernova remnant in supernova 1987A

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FOLLOWING an initial radio outburst[1] which decayed on a timescale of a few weeks, supernova 1987A[2] was undetectable at radio wavelengths until recently. In mid-1990, 1,200 days after the explosion, radio emission was once again detected[3] with the Molonglo Observatory Synthesis Telescope and the Australia Telescope Compact Array. Our observations since then show that the source has increased in strength at all monitored frequencies between 843 MHz and 8.6 GHz, with considerable variations in spectral index. The extended radio emission is centred within 0.5 arcsec of the optical supernova, and probably lies within the [O III] ring imaged by the Hubble Space Telescope. We interpret the emission as optically thin synchrotron emission from shock-accelerated electrons. This is the first time the birth of a nearby radio supernova remnant has been witnessed, and future observations will allow the structure of the remnant to be compared with the many other known radio remnants.

Since the demise of the initial radio emission, we have monitored SN1987A using the Molonglo Observatory Synthesis Telescope[4] (MOST) at 843 MHz and, since mid-1989, the Australia Telescope Compact Array[5] (ATCA) at 1.5, 2.4, 4.8 and 8.6 GHz. Renewed radio emission at the supernova position was first detected on 6 July 1990, using the MOST[3]. The flux density at this time was ~3 mJy. At higher frequencies, the onset of the radio emission was delayed, the first detection with the ATCA at 4.8 GHz being on 16 August 1990 (0.7 mJy). Since then, the MOST and the ATCA have made 70 and 40 observations, respectively. Each of these observations lasted ~12 hours. The MOST observations are affected by the strong source 30